Atmósfera 21(2), 213-223 (2008)

Variability of rainfall from tropical cyclones in northwestern México and its relation to SOI and PDO

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Received April 12, 2007; accepted October 22, 2007

RESUMEN

Los ciclones tropicales afectan la región semiárida del noroeste mexicano con una frecuencia alta durante septiembre, trayendo con ellos importante precipitación. El presente estudio se realizó para obtener un mejor conocimiento de la variabilidad interanual de los ciclones tropicales, sus relaciones con otros fenómenos oceánico-atmosféricos y su ocurrencia interdecadal. Se analizaron y utilizaron registros diarios de lluvia de 534 estaciones meteorológicas para calcular el porcentaje de precipitación anual relacionado con los ciclones tropicales del Pacífico nororiental que afectaron la región de 1949 a 2002. Utilizando técnicas de interpolación, las estaciones fueron agrupadas en áreas de $1° \times 1°$ y la forma en que los ciclones afectan las áreas se obtuvo utilizando el análisis de funciones empíricas ortogonales, con el que se pudieron identificar cinco regiones. Las series de variaciones interanuales representativas de cada región fueron analizadas para identificar cambios de la influencia de los ciclones tropicales en la lluvia anual. Se observó un gradiente en la influencia de los ciclones tropicales, declinando de sur a norte, principalmente en el área de la península. El cambio de régimen de 1976 es coincidente con un cambio de tendencia en las series de áreas con mayor influencia de ciclones tropicales. La influencia del índice de oscilación del sur (SOI, por sus siglas en inglés) es más fuerte en la parte norte de la región estudiada, mientras que la parte sur tiene una influencia más fuerte de la oscilación decadal del Pacífico (PDO, por sus siglas en inglés).

ABSTRACT

Tropical cyclones during September affect the semi-arid northwestern region of México with a relatively high frequency, bringing much-needed precipitation. This study provided a better understanding of tropical cyclone inter-annual variability, their relationships with other atmospheric-oceanic phenomena, and their inter-decadal occurrences. Daily rain data from 534 meteorological stations were analyzed and used to calculate the percentage of the annual precipitation related to tropical cyclones of the eastern North Pacific Ocean affecting the region from 1949 to 2002. Using interpolation techniques, the stations were grouped in $1° \times 1°$ areas, and the area structure of the tropical cyclone influence was obtained using empirical orthogonal function (EOF) variable analysis to identify five regions. Representative inter-annual variation series from each region were analyzed to identify changes in the influence of tropical cyclones as part of the annual precipitation. A gradient of tropical cyclone influence was found declining from south to north, mainly in the peninsula area. A regime shift in 1976 is coincident with a shift trend in series from areas with larger tropical cyclones influence. The Southern Oscillation Index (SOI) driving is stronger for the northern part of the region, while the southern part has stronger Pacific Decadal Oscillation (PDO) influence.

Keywords: Tropical cyclones, eastern North Pacific Ocean, precipitation, SOI, PDO.

1. Introduction

Tropical cyclones have a great effect on rainfall in northwestern México (Court, 1980; Douglas and Englehart, 1999), where the semi-arid climate is one of the most common features, with rainfall generally scarce and variable. There are two rainy seasons in this region; the winter rains occurring from November to February, where it is the larger part of the annual rainfall for the northern zone of the Baja California Peninsula, while the summer (monsoon and tropical storm rains appear from June to October and are dominant in the southern part of the region (Douglas and Englehart, 1995). Tropical cyclones affect the southern part of the region, mainly the southern half of the Baja California Peninsula, with highest frequency in September and October (Latorre and Penilla, 1988). Indeed, 40% of the tropical cyclones in the Northeast Pacific basin affect the Mexican coast, where Baja California Sur is the state with the higher risk of impact (Jáuregui, 2003). Several of these tropical cyclones trajectories move north and enter the Gulf of California, even reaching the southwestern United States, bringing with them considerable moisture (Martínez-Gutiérrez, 2004).

Tropical cyclones cause human and economic losses, but also produce beneficial rainfall (Court, 1980; Arroyo, 1982). It is necessary to improve interdecadal analysis of cyclonic events in Northwestern México to have a better understanding of the interannual variability of these meteorological events, their relationship with other atmosphere-ocean phenomena, and their historical tendencies.

Near-shore tropical storm activity is a very important component of the annual rainfall in the arid northwestern part of México. For example, during Hurricane Juliet (27 September to 3 October 2001), San Bartolo station (~23.75 °N, 109.18 °W), in the southeastern part of the Baja California Peninsula, received 815 mm rainfall in 3 days, when the annual mode is 400 mm and the mean is 319 mm. Even when the impact of a hurricane could bring disaster to communities from wind and rain damage, storm surges, and flooding, the greater rainfall is an opportunity to fill reservoirs and groundwater strata, which increases prosperity in the following year.

Tropical cyclones are not the only source of rainfall during the summer, sometimes coinciding with rain related to the Mexican monsoon (Douglas *et al*., 1993). Mesoscale convective system (MCS) originated over the Mexican mainland moved across the gulf overnight, bringing moisture over the peninsula (Farfán and Fogel, 2007).

Of the many relevant factors that have been linked to tropical cyclones, the foremost is El Niño-Southern Oscillation (ENSO), which has a substantial relationship to storms and can be used to provide seasonal forecasts of tropical cyclones (Landsea, 2000). However, fewer tropical cyclones seem to be associated with positive anomalies of the Southern Oscillation Index (SOI), one of the indices used to represent the ENSO for the years 1966-1979 (Reyes and Mejía-Trejo, 1991). Douglas and Englehart (1999) established that the strong El Niño decades of the 1980s and 1990s appear to have favored fewer storms passing into the central part of the peninsula.

Another index representing ocean-atmosphere variability is the Pacific Decadal Oscillation (PDO), which has been detected and quantified as the sea surface temperature anomaly across the extra-tropical Pacific (Mantua *et al*., 1997). Its signal has been related to runoff in the Gulf of California continental watershed (Brito-Castillo *et al*., 2003), but has not yet been related to tropical cyclone activity. The oceanographic literature reports the shift as a change in the intensity of the Aleutian low pressure regime in 1976-1977, which was associated with a major and persistent change in oceanographic conditions (Graham 1995; Miller *et al*., 1994). The term “regime” has been used to denote multi-decadal periods separated by shifts (Ware, 1995), where the most-documented regime shifts occurred around 1976. Changes in environmental and biological variables have been related to this event (Englehart and Douglas, 2001; Lluch-Belda *et al*., 2001). Other proposed dates of climate shifts are 1925, 1947, and 1989 (Mantua *et al*., 1997); however, the shift in 1989 is not as clear (Hare and Mantua, 2000). There are no studies relating this to tropical cyclone frequency.

There is some debate over whether global climate change that results in increased sea surface temperature (SST) will lead to more frequent or intense tropical storms (Andrade and Sellers, 1988; Curry *et al*., 2006), but the SST is not the sole controlling factor of intensity, since it is the result of a complex interaction between the internal dynamics of the system and the environmental factors surrounding the storm and atmospheric structure affecting steering winds at higher altitudes (Witney and Hobgood, 1997; Michaels *et al*., 2006).

Long term studies of tropical cyclones (1896-1995) did not find an increased signal in frequency or intensity for the Gulf of México (Bove *et al*., 1998); however, Newman (1993) found that from the late 1960s onwards, the subtropical, northeastern Pacific experienced a significant upward trend in tropical cyclones, and admits that variability is completely unknown because of the lack of a long, reliable record. Jáuregui (2003) found an increase in tropical cyclones during the 1990 decade for the Pacific coast of México. Overall, these suggested changes are quite small compared to the observed large variability in tropical cyclones. These ambiguous issues suggest that more studies covering longer time periods are needed to understand the complex interaction between these storms and the tropical atmosphere-ocean.

This paper attempted to clarify inter-annual and inter-decadal variability of tropical cyclone influence in northwestern México between 1949 and 2002 by analyzing daily rainfall and establishing relationships with different decadal and inter-decadal indices of large-scale ocean-atmosphere phenomena.

2. Data and methods

The tropical cyclone tracking data were taken from the Unisys Weather hurricane/tropical data set (http://weather.unisys.com/hurricane/index.html). All tropical cyclones with a path within 2° (216 km) of Northwestern México (the Baja California Peninsula, Sonora, and Sinaloa) from 1949 to 2002 were selected.

Daily precipitation data from 534 meteorological stations with Northwestern México were obtained from the Servicio Meteorológico Nacional. We calculated the percentage of the annual rainfall related to tropical cyclones for each station by summing the rainfall volume that was recorded on the days that a tropical cyclone was within this region. This is an underestimate of cyclone-related precipitation because the storm remnants can generate large amounts of precipitation in the days after the tropical cyclone track is farther than 216 km from the region.

The PDO index developed by Mantua *et al*. (1997) was considered the first principal component of North Pacific monthly SST variability. The data were available in electronic format (http://www.jisao.washington.edu/pdo/). We calculated an annual and seasonal average of the PDO index (winter rainy season, November through February; dry season March through June, and summer rainy season, July through October). The SOI is the index that measures the differences in air pressure between Tahiti and Darwin, Australia. Using these records, a correlation between a SOI index and rainfall was possible. SOI data were obtained at: http://www.longpaddock.qld.gov.au/SeasonalClimateOutlook/SouthernOscillationIndex/SOIDataFiles/index.html. We used annual and seasonal average indices.

The records of the meteorological stations have irregularities, start in different year, and have missing data. To resolve these problems, we grouped the stations into sixty-eight 1° × 1° sectors, and, for each one, computed a representative series by interpolation. This procedure included the centroid area distance:

$$d_i = \otimes\, (x_2 - x_1)^2 + (y_2 - y_1)^2,$$

where x_1 and y_1 are the centroid coordinates (x and y are the average of the stations within the sector), and x_2 and y_2 are coordinates of the stations. The area-representative series were obtained by:

$$P't = \sum(1/d_i)p_i \,/\, \sum(1/d_i),$$

where $P't$ is the annual percentage of precipitation from tropical cyclones by sector for year t, p_i is the annual percentage of precipitation that might be attributed to the tropical cyclones for station i grouped in its sector, and d_i is the centroid parameter. We used rainfall data from 1941 to 2001 for the period with more records; however eight sectors were discarded because they involved stations with incomplete records.

The regional structure of the influence of tropical cyclones was calculated with the varimax rotated empirical orthogonal function analysis (EOF-var), which is based on a covariance matrix of $P't$, using Statistica software (Statsoft, 1995; Comrie and Glenn, 1998). Five loading factors explained 92% of the variation in the original data. Spatial distribution was determined with the series, where the loading values were > 0.7 for each factor. By averaging the series of a factor, we obtained a representative series for each sector. These series were correlated with annual and seasonal PDO and SOI indices.

The inter-annual variation series were standardized to obtain anomalies and the cumulated differences were integrated to identify long-term trends of tropical cyclone influence on annual precipitation.

3. Results

The EOF-var modes represent sub sectors in northwestern México, within which tropical cyclone influence on annual precipitation exhibits high levels of intercorrelation (Fig. 1). We identified five areas: Sinaloa-Sonora or continental area (CON); the northern part of the Baja California Peninsula or area coinciding with Mediterranean climate (MED); the middle part of the peninsula (MID); the southern-most part of the peninsula called the Los Cabos area (LCB); and an area between the middle part and the southernmost part of the peninsula and a small area on the mainland in Sonora called Mixed (MIX).

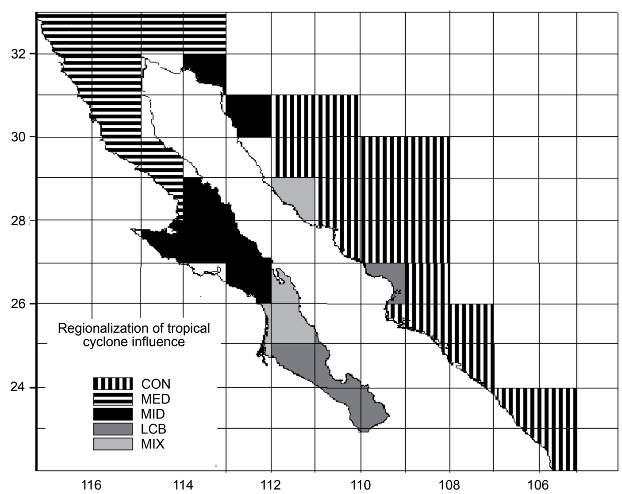

Fig. 1. Influence of tropical cyclone regionalization in northwestern Mexico. The squares without hachures lack meteorological stations with sufficiently long records.

LCB is the area with the most tropical cyclone influence on annual rainfall (Table I). This includes the Guaymas area in Sonora. Guaymas has been linked with the southernmost part of the Baja California Peninsula in other biogeographic (Álvarez-Castañeda, 1994) and ecological studies, suggested by the similarity in vegetation physiognomy (León de la Luz, pers. comm.).

Table I. Descriptive statistics of the representative series of the annual percentage of precipitation from tropical cyclonic influence for each area.

Region	Maximum	Minimum	Mean	S. D.	Slope
CON	39	0	14	10	0.4
MED	25	0	4	5	0.0
MID	41	0	13	10	0.3
LCB	67	3	27	15	0.5
MIX	65	2	17	11	0.4

Representative series of *P't* from each area (Fig. 2) show annual percentage changes of rainfall resulting from tropical cyclones. Even when the CON area has a strong tropical cyclone influence, as occurred during 1950s and 1960s, its precipitation series showed low variability. MED, the most northwestern area has the lowest impact from tropical cyclones (Table I) and is the area with the lowest inter-annual variability. The LCB series has the highest variability and a general positive tendency. The series of SOI and PDO are also shown in Figure 2.

To evaluate the relationship between number of tropical cyclones with *P't*, each series were correlated with the number of tropical cyclones from 1963 to 2002 (Table II). The correlation was significant with CON, LCB, and MIX, the areas with higher tropical cyclone influence in the region.

When a correlation matrix was developed for these series, the CON, LCB, and MIX series had significant correlations between them, related to their position in the southern part of the region, where tropical cyclone frequency is higher. The CON and LCB areas have a significant correlation with the PDO index series ($r = 0.40$ and $r = 0.37$, respectively, and $p < 0.005$ for both correlations). The SOI winter index has a significant correlation with the MED area ($r = 0.32$, $p < 0.05$). These results are in accord with Pavía and Badan (1998).

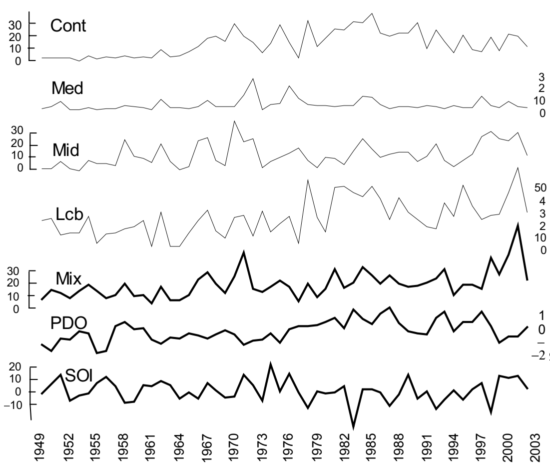

Fig. 2. Annual values of percentage of precipitation associated with cyclones in each area (the y-axis is alternated from right to left to avoid crowding), as well as annual PDO and November-February SOI series.

Table II. Correlation coefficient between each *P't* series with the number of tropical cyclones (TC) from 1963 to 2002.

Region	TC	p-level
CON	0.66	0.000
MED	0.41	0.007
MID	0.19	0.233
LCB	0.36	0.023
MIX	0.38	0.016

Accumulated anomalies were used to identify changes in tendency in the influence of tropical cyclones on annual precipitation of the series, with significant correlations with the previous analyses (Fig. 3). Accumulated anomalies from the SOI indices have an opposite tendency in the respective PDO series. CON and LCB-accumulated tendencies have a similar negative tendency from 1941 to the middle of the 1970s, and then change to a positive tendency. Their correlation coefficient with the PDO-accumulated anomalies indices are high ($r = 0.86$ and $r = 0.91$ for the two series and $p < 0.05$ for both cases). MED has a particular pattern. This is the only series exhibiting significant correlation with the SOI series. It has a negative tendency, like the PDO, from 1941 to 1970. After that, it is more like the SOI tendency. From Figure 3, we concluded that the influence of the SOI and PDO is not the same for the whole of the analyzed period series. Table III shows the SOI having greater influence in the MED area from 1970-1980; the PDO for CON and LCB has greater influence for the entire period. In a separate analysis, the PDO-accumulated anomaly series from 1900-2004 (Fig. 4) has the greatest influence in the region during the period when the slope of that curve is negative.

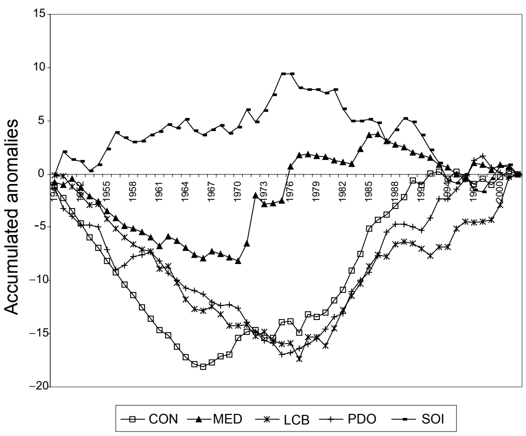

Fig. 3. Accumulated anomalies for selected sectors series and PDO and SOI accumulated anomalies. The selected series were those having significant correlations with PDO or SOI indices.

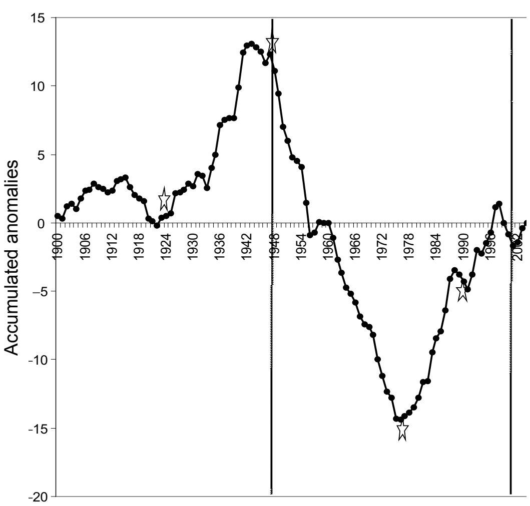

Fig. 4. PDO-accumulated anomalies (1899-2004). Analysis for this study is from 1949 to 2002. Regime shifts are indicated by stars (source: Mantua *et al*., 1997)

Table III. Correlation coefficient between PDO and sector PPT-dependence on tropical cyclones for different time intervals. Values higher than 0.33 are significant at $p < 0.05$.

	Interval	CON	MED	MID	LCB	MIX
PDO	1949-1960	0.26	0.00	0.52	0.27	0.24
	1960-1970	0.08	–0.49	–0.16	0	0.02
	1970-1980	–0.17	–0.25	–0.31	0.05	–0.62
	1980-1990	–0.13	–0.02	0.26	0.10	0.39
	1990-2002	–0.05	0.22	–0.14	–0.17	–0.33
Cool	1949-1976	0.00	–0.04	0.11	0.05	–0.07
Warm	1976-2002	0.20	–0.01	–0.13	0.00	–0.18
Cool/warm	1949-2002	0.38	–0.02	0.12	0.38	0.12
SOI	1949-1960	–0.05	0.30	–0.34	–0.19	–0.23
	1960-1970	–0.29	0.48	0.04	0.26	–0.05
	1970-1980	–0.25	0.45	0.07	–0.45	0.3
	1980-1990	–0.19	0.23	–0.03	–0.01	–0.05
	1990-2002	–0.43	0.34	0.25	0.41	0.27
Cool	1949-1976	0.09	0.42	0.03	0.04	0.2
Warm	1976-2002	–0.36	0.36	0.16	0.03	0.13
Cool/warm	1949-2002	–0.24	0.32	0.05	–0.09	0.08

4. Discussion and conclusion

Our analysis of the precipitation series related to tropical cyclones from 1949 to 2002 (from 534 meteorological datasets, grouped into 60 areas) indicated that there are five subregions of tropical cyclone influence within northwestern México. Also, there is a gradient of effect of tropical cyclone from south to north, mainly in the Baja California Peninsula. Few tropical cyclones track into the Gulf of California and the moisture reaching continental areas on the east side of the gulf is less intense than in the LCB and MIX areas, but is more than what occurs in the MID and MED areas. Areas with a correlation amongst them (CON, LCB, and MIX) indicate a synchronic pattern resulting from tropical cyclone activity at the interdecadal scale.

The shift in regime in 1976 is coincident with a shift in the trend in the areas that are more strongly influenced by tropical cyclones (Fig. 3), but it is not clear whether a shift occurred at the end of the century. The impact of tropical cyclones on annual precipitation increased between 1976 and the early 1990s (regime shift), but since that time the impact of tropical cyclones in these areas seem to have diminished.

The correlation between CON and LCB with PDO ($r = 0.38$; $n = 58$, $p < 0.005$ in both areas) suggests a larger contribution of tropical cyclones on the annual precipitation in northwestern México during the positive phase of the PDO (and in phase with ENSO), than during the negative phase of the PDO. This is due to more cyclone-related precipitation, and it agrees with previous studies related to the positive phase of PDO signal, which increases the runoff in the Gulf of California continental watershed (Brito-Castillo *et al*., 2003). However, since the 1990s the tendency is not clear.

Even though it is not the intent of this study, we believe that the information published on the secular variation is not clear about the tendency of the effect of tropical disturbances on tropical cyclones in a period of global warming (Salinas-Zavala, 2000).

Winter is the most important season of precipitation in the MED area of the northern Baja California Peninsula, which makes the impact of rainfall from tropical cyclones from May to November more evident. The analyses show that the ENSO teleconnection is stronger for the northern part of this region, while the southern part has a stronger PDO teleconnection. That variability over a smaller geographic scale illustrates the transitional climate character of northwestern México.

From a simplistic view, SST is the physical mechanism through which PDO and ENSO are associated with the tropical cyclone variability, and like the region, is in a transitional climate zone where the differential effect of the climatic phenomena in time and space is more evident. Using those climatic indices lets us explore interannual and interdecadal scales.

Acknowledgments

We thank L. Huato at CIBNOR for his assistance with the interpolation technique, W. L. Hamilton at CICESE for his comments, as well as the Servicio Meteorológico Nacional for the climate data.

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